Issues for the Lattice in Hadron Spectroscopy

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Lattice QCD predicts a rich spectroscopy of glueballs and $q\bar{q}-$glue hybrids. I compare these with data and assess the emerging empirical situation. Questions for the lattice are proposed.

1. The Glue Landscape

The collective behaviour of gluons in the strong interaction regime of QCD is one of the black holes of the standard model. Lattice QCD and a range of QCD inspired models all suggest that the lightest glueballs occur in the 1-2 GeV region and that $q\bar{q}-$gluon hybrids occur around 2 GeV in mass, yet, a quarter of a century after QCD was developed,their existence is not yet definitely established.

The PDG[1] have extensive lists of meson properties. These states fit well with a naive $q\bar{q}$ spectroscopy, at least up to around 2 GeV, without any clear evidence or need for extra glueballs. While it may be the case that the emergence of a glueball spectrum above 2 GeV disturbs and complicates the $q\bar{q}$ picture, the prediction that $J^{PC} = 0^{++}$ occurs **below** 2 GeV, and moreover around 1.6 GeV, ought to be testable. For if we cannot establish the truth or otherwise of this, what hope do we have to establish the existence of strongly bound glue in general?

A reason why so much is known about $q\bar{q}$ states is due to the emphasis through several decades on beams of π, K, p made of quarks interacting with targets made of quarks which biased the production of $q\bar{q}$ states. A further bias was the historical emphasis on detecting decays into charged particles such as $\pi^{\pm}, K^{\pm}$ and inability to detect easily η or η' whose affinity for glue via the $U_A(1)$ anomaly had been speculated. Thus I suggested[2,3] that glueball signals may be enhanced if one concentrated on production in a quark-free environment and if one also studied decay channels involving $\eta\eta$ and $\eta\eta'$ or even $\eta'\eta'$.

Three optimal production strategies were suggested.

i) $\psi \to \gamma R$[4] where, in pQCD, the $\psi(c\bar{c}) \to \gamma gg \to \gamma R$. The intermediate gg system favours states coupling to glue.

ii) Central production, $pp \to p + R + p$, where the resonance R is produced displaced from the beam and target in rapidity as $s \to \infty$. The idea is that diffractive processes are driven by gluons (the Pomeron)[5].

iii) $p\bar{p}$ annihilation at low energies, where $(qqq) + (\bar{q}\bar{q}\bar{q}) \to \pi + gg$, and subsequent detection of etas (hence $p\bar{p} \to \pi\eta\eta$ or $\pi\eta\eta'$) appeared to me to be a natural source of a $J^{PC} = 0^{++}$ or 2^{++} in the 1-2 GeV region. The emergence of LEAR and especially the Crystal Barrel seemed particularly suitable[2].

Meanwhile, lattice QCD predictions for the mass of the lightest scalar glueball were maturing. To set the scene here is a summary of what lattice QCD predicts.

1.1. Glueballs

The SU(3) glueball spectrum for all J^{PC} values at lattice spacings down to $\beta = 6.4$ has been studied by ref.[6]. The generic features include

i) the lightest state has $J^{PC} = 0^{++}$ with $m \sim 1.6 \pm 0.1$ GeV.

ii) Below 3 GeV, potentially accessible in $\psi \to \gamma G$, there are also $J^{PC} = 0^{-+}, 2^{++}$ and possibly also $J^{PC} = 2^{-+}$ and the spin exotic $J^{PC} = 1^{-+}$.

iii) There are signals for spin exotics, $J^{PC} = 0^{+-}, 1^{-+}$ and possibly 0^{--}, below 4 GeV.

The predictions for the mass of the lightest scalar glueball have become firmer at this conference[7].

1.2. Hybrids

The spectrum of hybrid mesons produced by gluonic excitations in quenched QCD has been evaluated[8,9]. The most clear cut signal for a hybrid meson is to search for J^{PC} quantum numbers not allowed in the quark model such as $J^{PC} = 1^{-+}, 0^{+-}$ and 2^{+-}. Light flavoured hybrids are predicted to contain $J^{PC} = 1^{-+}$ with mass 2.0 ± 0.2 GeV[8] (for the $s\bar{s}$ so the $n\bar{n}$ may be expected some 200-300 MeV lower) in agreement with $1.97 \pm 0.09 \pm 0.3$(syst) GeV[9]. Heavy flavour hybrids include $c\bar{c}g$ at 4.19 ± 0.15 GeV[8]. Ref.[9] find $J^{PC} = 1^{-+}$ at $4.39 \pm 0.08 \pm 0.2$ GeV with the $J^{PC} = 0^{+-}$ higher at ~ 4.6 GeV. The $b\bar{b}g$ hybrids are predicted to be slightly above the $\Upsilon(4S)$ at 10.81 ± 0.25GeV[8].

What evidence is there for any of these states being realised in Nature? There have been some exciting developments in the last three years. These have been stimulated by the clear sighting of a scalar flavourless meson $f_0(1500)$ that is, at least superficially, a glueball candidate and of flavoured mesons $\pi(1800)$ and exotic $J^{PC} = 1^{-+}$ with properties consistent with being quark-gluon hybrids. The plan of the talk will be to survey the primary glueball candidates $f_0(1500)$ and $f_{(J=0,2?)}(1710)$, then address other possible states with the lattice and finally look at the hybrid meson scenario.

2. The Scalar Glueball and the $f_0(1500)/f_J(1710)$

A novel $J^{PC} = 0^{++}, m \simeq 1.5$ GeV, $\Gamma \sim 100$ MeV appears to be present in each of the three processes cited above as "glueball friendly". A state denoted $f_J(1710)$[1] (where $J = 0$ or 2) also is seen tantalisingly in $\psi \to \gamma f_J$, in central production $pp \to pf_Jp$ and, recently, in $p\bar{p}$ annihilation in flight. In recent months two further processes have come into attention, each involving heavy flavours

a) $D_s \to \pi\pi\pi$ where $D_s(\bar{s}c) \to W^+gg \to \pi^+(\pi\pi)$. This can complement $D_s \to \pi(K\bar{K})$ and help establish the flavour content of 0^{++} mesons.

b) $B \to K + (c\bar{c}) \to Kgg \to K+$ light hadrons. This might provide an entree into the glueball sector and possibly also $c\bar{c}g$ hybrid charmonium, up to ~ 4 GeV[10].

A significant new result from the lattice[11] is that the two body width of a scalar glueball is $\sim O(100)$ MeV and not $\sim O(1000)$ MeV. In principle the glueball could have been extremely wide and for practical purposes unobservable. The lattice shows that the scalar glueball should be a reasonably sharp signal which is an important guide in helping to eliminate candidates. The width for decay of the scalar glueball into pseudoscalar pairs was predicted[11] to be 108 ± 28 MeV. The $f_0(1500)$ has $\Gamma_{tot} = 120 \pm 20$ MeV[1] with the decays into pseudoscalar pairs comprising ~ 60 MeV of this. The $f_J(1710)$ has $\Gamma_{tot} = 140 \pm 12$ MeV, prominently in 0^-0^-. The lattice prediction of the width guides us towards these states (if $f_J(1710)$ has $J = 0$) but does not of itself discriminate between them.

I shall begin by reviewing the data on the $f_0(1500)$ and $f_J(1710)$ in the three "classical" processes above.

2.1. $p\bar{p}$ annihilation

A basic template in $pQCD$ is the $q\bar{q}g$ vertex as manifested in three-jet events, $e^+e^- \to q\bar{q}g$. To form the simplest $(gg)_1$ gluonic system (where the subscript denotes the colour representation) requires $(qq)_{\bar{3}} + (\bar{q}\bar{q})_3 \to (gg)_1$. The only diquark "beams" are contained within baryons and so we focus on $p\bar{p} \to \pi + (gg)_1 \to \pi(\eta\eta)$ and other relevant channels. Prior to LEAR there were few events on these channels; post LEAR there are millions of events and it is this fact, combined with the high resolution of the Crystal Barrel detector in particular, that has revolutionised our picture of hadron spectroscopy in the critical region of $\sim 1.5 - 2$ GeV.

If a $J^{PC} = 0^{++}$ glueball really exists below 1.7 GeV, then the above suggests that it must be produced by $p\bar{p}$ at rest. There seemed to be only two possible problems that might obscure it: (i) if the width is huge (recent lattice results suggest that this is unlikely[11,12]) (ii) if the qqq and $\bar{q}\bar{q}\bar{q}$ rearrange themselves to form 3π as a background swamping any $\pi + G$ signal. The vast data sample with high resolution from both Crystal Barrel and Obelix has overcome the latter problem.

There is one final problem. Established states

such as K_0 (1430), f_0 (1370) (and subsequently a_0 (1450)[1]) and/or $q\bar{q}$ potential models imply that the $J^{PC} = 0^{++}\ {}^3P_0 q\bar{q}$ nonet is expected to occur in the vicinity of the primitive scalar glueball. There will be mixing between the $n\bar{n}, G_0$ and $s\bar{s}$ states[13]. The resulting mixing pattern is rather robust when extended to a full 3x3 mixing[12,14,15] and has the following consequences. Three physical states will occur that we refer to as ϕ_s, ϕ_G, ϕ_n which we identify as $f_0^n \simeq 1370, f_0^{G/s} \simeq 1500, f_0^{s/G} \simeq 1700$ (the latter state may be the f_J (1710) or it may be shifted strongly by coupling to $K\bar{K}$ in $S-$wave and thereby be associated with f_0 (980). This is currently a hotly debated topic. The empirical situation is as follows.

The $f_0(1500)$ is seen in $p\bar{p} \to \pi\eta\eta, \pi\eta\eta', \pi\pi\pi$ and 5π. There are also emerging signs in $\pi K\bar{K}$. The state clearly exists. An extensive review of its properties in $\bar{p}p$ is given by Amsler[16]. See also ref.[13,12]. The suppression of $K\bar{K}$ and affinity for $\eta\eta$ and $\eta\eta'$ are consistent with the $G - q\bar{q}$ mixing[13]. The mass and width are typically $m = 1500 \pm 15, \Gamma = 120 \pm 15$ MeV. Little is yet known about $f_J(1710)$ in $p\bar{p}$ as most data have been taken at rest where phase space kills $f_J(1710) + \pi$; data in flight see a signal but a separation of $J = 0, 2$ remains to be made.

2.2. Production in $\psi \to \gamma R$

Ref.[14] has used the measured radiative quarkonium rates and $\gamma\gamma$ decay widths to make quantitative estimates of the gluonic content of isosinglet mesons. In essence, it describes the empirical $b.r.(\psi \to \gamma R)$ as a convolution between a piece calculable in pQCD and a residual non-perturbative unknown that is essentially the $b.r.(R \to gg)$. One may expect

$$b(R[q\bar{q}] \to gg) = 0(\alpha_s^2) \simeq 0.1 - 0.2$$

$$b(R[G] \to gg) \simeq 0(1)$$

Thus knowledge of $b(R \to gg)$ would give quantitative information on the glueball content of a particular resonance.

Ultimately the proof of the pudding is in the eating. A priori one could imagine that the extracted $b(gg)$ could be anything at all, greater than 100% even, if the idea had no foundation.

However, when applied to known $q\bar{q}$ resonances one finds

$$b.r.[f_2(1270), f_2(1525), f_1(1280), f_1(1420), \eta(1285)]$$

$$\simeq 0.2 - 0.3 \simeq O(\alpha_s^2)$$

This contrasts with $br(\xi(2230)) \simeq 1; br(\eta(1410)) \simeq 0.9$ and $br(f_0(1500)) \simeq 0.6$ (assuming that the signal in $\psi \to \gamma 4\pi$ is indeed $J^P = 0^+$ as claimed by[17] and not $J^P = 0^-$; this needs to be clarified at Beijing and at a Tau Charm Factory) and $br(f_J(1710)) \sim 0.8$ if $J = 0$.

The 3×3 mixing schemes give a picture where the branching ratios are expected to be (in units 10^{-3})[14]

$$b(\psi \to \gamma f_0(1370) : \gamma f_0(1500) : \gamma f_0(1700))$$

$$\simeq 0.2 : 0.5 : 1 \tag{1}$$

which appear to be consistent with an analysis of $\psi \to \gamma\pi\pi$ and $\gamma K\bar{K}$[20]. A general summary of glueball candidates, when confronted quantitatively with $\psi \to \gamma R$ is as follows.

(i) The $f_0(1500)$[13,14,17] is probably produced at a rate too high to be a $q\bar{q}$ state. The average of world data suggests it is a glueball-$q\bar{q}$ mixture.

(ii) The $f_J(1710)$[18] where $J = 0$ or 2[1] is produced at a rate which is consistent with it being $q\bar{q}$, only if $J = 2$. If $J = 0$, its production rate is too high for it to be a pure $q\bar{q}$ state but is consistent with it being a glueball or mixed $q\bar{q}$-glueball having a large glueball component[14,20].

(iii) The $\xi(2230)$[21], whose width is ~ 20 MeV, is produced at a rate too high to be a $q\bar{q}$ state for either $J = 0$ or 2. If $J = 2$, it is consistent with being a glueball. The assignment $J = 0$ would require $Br(J/\psi \to \gamma\xi) \sim 3\ 10^{-4}$, which already may be excluded.

(iv) The enhancement once called $\eta(1440)$ has been resolved into two states[14,19]. The higher mass $\eta(1480)$ is dominantly $s\bar{s}$ with some glue admixture, while the lower state $\eta(1410)$ appears to have strong affinity for glue.

2.3. Suppression in $\gamma\gamma$

By contrast, the $\gamma\gamma$ couplings are expected to be small for a glueball and in the mixed states of

refs.[13,12] we expect the relative magnitudes of their production rates as follows[14]

$$\Gamma(\gamma\gamma \to f_0^{nn} : f_0^G : f_0^s) \simeq 5 : 0.1 - 0.4 : 1 \qquad (2)$$

If the empirical width $f_0(1370) \to \gamma\gamma \simeq$ 2-5 keV then the $\Gamma(f_0(1500) \to \gamma\gamma) \simeq$ 0.03-0.4 keV is the challenge for experiment. An optimal strategy for searching for the $s\bar{s}$ member of the multiplet is to study $\gamma\gamma \to f_0 \to K\bar{K}$ or $\eta\eta$ (also one should study $D_s \to \pi K\bar{K}$, see later). Hints from LEP2 are that $\gamma\gamma \to f_0(1500) \to \pi\pi$ implies that $\Gamma(f_0(1500) \to \gamma\gamma) \le 0.17$keV[23]

2.4. Scalar Mesons in D_s decays

D_s decays can provide a direct window into the 0^{++} sector. Qualitatively one expects a hierarchy

$$\Gamma(D_s \to \pi(s\bar{s})) > \Gamma(D_s \to \pi gg \to \pi G) >$$

$$\Gamma(D_s \to \pi gg \to \pi(n\bar{n}))$$

Empirically in $D_s \to \pi\pi n$ one sees πf_0 (980) as most prominent which is presumably due to the affinity of f_0 (980) for $s\bar{s}$, or $K\bar{K}$. The empirical hierarchy from E687 is, roughly, for the $\pi\pi\pi$ channel

$$b.r.(D_s \to \pi f_0(980) : \pi f_0(1500) : \pi f_2(1270) : \pi\rho)$$

$$\simeq 0.65 : 0.25 : 0.08 : 0.02$$

The $\pi f_2(1270)$ is probably driven by $\pi gg \to \pi(n\bar{n})$ whereas $\pi\rho$ comes from annihilation $D_s \to W \to \pi_g$[24]. The observation of f_0 (1500) (the fit requires $M= 1475$, $\Gamma = 100$ which is well consistent with the f_0 (1500)) is interesting as is its production rate. An analysis of $D_s \to \pi(gg) \to \pi R$ along the lines of ref.[14] could be informative. It is now important also to study $D_s \to \pi K\bar{K}$ and $\pi\eta\eta$ in order to access the $s\bar{s}$ number of the $J^{PC} = 0^{++}$ nonet and help to elucidate the nature of f_0 (1500) and f_J (1720). In particular it will be central to determining if $f_0(980)$ is the only state below $\sim$ 1800 MeV that couples strongly to $s\bar{s}$: this could have major implications for establishing the $s\bar{s}$ content of the $^3P_0$ nonet.

2.5. Central Production

In $pp \to p(4\pi)p$ and $p(2\pi)p$, WA91 and WA102[26] see a scalar signal in the 1500 MeV region. However this cannot be immediately claimed as support for a glueball since, in the 4π spectrum at least, the most prominent structure is the f_1 (1285), a well established $q\bar{q}$ state. Thus we infer that both $q\bar{q}$ and G can be produced and that there may be interference between the $^3P_0 q\bar{q} f_0$ (1370) and a glueball candidate f_0 (1500). Indeed there does appear to be non-trivial interference since the mass and/or width are not simply identified with those of the f_0 (1500) ($m \sim 1500, \Gamma \sim 100 MeV$). WA91 found

$i)$ in$2\pi : m = 1500 \pm 30 MeV$ $\Gamma = 200 \pm 30 MeV$

$ii)$ in$4\pi : m = 1445 \pm 5 MeV$ $\Gamma = 65 \pm 10 MeV$

Clearly central production is not simply a glueball factory and we need to look into it more critically.

3. How to Make Glueballs when Protons Collide

Feynman imagined two protons colliding in their c.o.m. Each proton consists of partons carrying longitudinal momentum functions $0 \le x \le 1$. Those with $x \to 1$ are clearly right or left movers in the c.o.m. and unambiguously belong to the right or left moving proton respectively. However those with $x \to 0$ in either left or right mover are (near) at rest in the c.o.m. and can transfer from left to right moving proton without disturbing the protons' wavefunctions. In Feynman's picture it is the exchange of these $x \to 0$ partons that is responsible for elastic scattering.

Measurement of the parton distribution functions show that as $x \to 0$ the partons are most likely to be gluons. Thus we may envision elastic scattering at high energies as mediated by the exchange of gluons in an overall colour singlet configuration.

Now consider the exchange of partons (gluons) with $x_{1,2} \neq 0$. The two gluon beams may fuse to produce a meson whose overall momenta will be

$$p_L \equiv (x_1 - x_2)P; p_T \equiv q_{1T} + q_{2T}$$

and for $x_1 \simeq x_2$ the mass will be

$$M_R^2 \simeq 4x_1 x_2 P^2 - P_T^2 \simeq 4x_1 x_2 P^2$$

(where the experimental conditions are typically $4P^2 \equiv s \simeq 900$ GeV^2 and the M_R^2 range of interest is 1-4 GeV^2). To form an exclusive meson the relative momentum of the incident gluon "beams", namely $(x_1+x_2)P \simeq 2x_1 P \simeq M_R$, must be redistributed so that the constituents of the produced meson have a **small** relative momentum $\lesssim 0(\Lambda_{QCD})$. Thus considerable rescattering will be required, especially at large M_R, and so one expects that the gluons may fuse directly into a glueball or may undergo $gg \rightarrow q\bar{q}$ and form a quarkonium.

The question that Kirk and I addressed is whether one may alter the kinematic conditions and enhance the glueball production relative to $q\bar{q}$. We suggested that one study the spectrum as a function of[27]

$$dp_T = |\vec{q}_{T1} - \vec{q}_{T2}|$$

since, for a given M_R, when $|dp_T|$ is large, more rescattering is required (in the transverse direction) than when $|dp_T|$ is small. Thus for $|dp_T|$ small one may hope that glueballs may be more favoured; for $|dp_T|$ large, by contrast, the $q\bar{q}$ may be relatively enhanced. Refs.[27,22] and found that all undisputed $q\bar{q}$ mesons are suppressed at small dp_T whereas glueball candidates are enhanced. Specifically,

(i)when $dp_T > 0.5$ GeV/c the $q\bar{q}$ states f_1 (1285) and f_1 (1420) are clearly seen in the $K\bar{K}\pi$ channel; when $0.2 < dp_T < 0.5$ GeV the $q\bar{q}$ are still visible, though rather less prominent, whereas for $dp_T < 0.2$ GeV they have all but disappeared into the background.

(ii)The $f_2(1270)$ and $f_2(1525)$ show similar behaviour in the $\pi\pi$ and $K\bar{K}$ channels respectively: they only become apparent as dp_T increases.

(iii) In the $K\bar{K}$ spectrum it is also noticeable that the $q\bar{q}$ f_2 (1525) is produced dominantly at high dp_T whereas the enigmatic f_J (1710) is produced dominantly at low dp_T.

(iv) The 4π channel is particularly rich. At large dp_T the $q\bar{q}$ $f_1(1285)$, $\eta_2(1700)$ and possibly $f_4(2040)$ are seen with the $f_1(1285)$ particularly sharp. However, when $dp_T < 0.2$ GeV

the f_1 (1285), a $q\bar{q}$ state, has essentially disappeared as do the η_2 and f_4 while the f_0 (1500) and an enigmatic f_2 (1900) structure have become more clear. These surviving structures have been identified as glueball candidates: the f_0 (1500) is motivated by lattice QCD while the f_2 (1900) is noted to have the right mass to lie on the Pomeron trajectory[30].

Thus we have a tantalising situation in central production of mesons. We have stumbled upon a remarkable empirical feature that does not appear to have been noticed previously. Although its extraction via the dp_T cut was inspired by intuitive arguments we have no simple dynamical explanation. An interesting question is whether similar phenomena occur in $ep \rightarrow eRp$ or $e^+e^- \rightarrow e^+Re^-$. These can be investigated at HERA or in e^+e^- colliders if the outgoing beams are tagged[29].

The $f_0(1500)$ shares features expected for a glueball that is mixed with the nearby isoscalar members of the $^3P_0$ $q\bar{q}$ nonet. In particular ref[13] noted that this gives a destructive interference between $s\bar{s}$ and $n\bar{n}$ mixing whereby the $K\bar{K}$ decays are suppressed. The properties of the $f_J(1710)$ become central to completing the glueball picture. If the $f_J(1710)$ proves to have $J = 2$, then it is not a candidate for the ground state glueball and the $f_0(1500)$ will be essentially unchallenged. On the other hand, if the $f_J(1710)$ has $J = 0$ it becomes a potentially interesting glueball candidate. Indeed, Sexton, Vaccarino and Weingarten[11] argue that $f_{J=0}(1710)$ should be identified with the ground state glueball, based on its similarity in mass and decay properties to the state seen in their lattice simulation. The prominent scalar $f_0(1500)$ was originally interpreted by them[11] as the $s\bar{s}$ member of the scalar nonet, however this identification does not fit easily with the small $K\bar{K}$ branching ratio and the dominant decays to pions.

Whereas the spin of the $f_J(1710)$ remains undetermined, it is now clearly established that there are scalar mesons $f_0(1370)$ and $f_0(1500)$ [1] which couple to $\pi\pi$ and $K\bar{K}$ and so must be allowed for in any analysis of this mass region.

The presence of $f_0(1370), a_0(1450), K_0(1430)$ reinforce the expectation that a $q\bar{q}$ $^3P_0$ nonet is

in the $O(1.3 - 1.7)$GeV mass region. It is therefore extremely likely that an 'ideal' glueball at ~ 1.6GeV [15] will be degenerate with one or other of the $^3P_0$ states given that the widths of the latter are O(hundreds MeV). This has not been allowed for in any lattice simulation so far.

The emerging concensus is that the scalar glueball is not a singleton and that there are significant gluonic components in the nearby $n\bar{n}$ and $s\bar{s}$ states. Ref.[13] proposed that "if the $f_J(1710)$ is confirmed to have a $J = 0$ component in $K\bar{K}$ but not in $\pi\pi$, this could be a viable candidate for a $G_0 - s\bar{s}$ mixture, completing the scalar meson system built on the glueball and the quarkonium nonet".

Recently Weingarten[12] has proposed what at first sight appears to be a different mixing scheme based on estimates for the mass of the $s\bar{s}$ scalar state in the quenched approximation. Whereas ref[13] supposed that the ideal glueball lies within the nonet, ref[12] supposed it to lie above the nonet. I shall now start with the general expressions of ref[13] and compare the two schemes. This will reveal some rather general common features.

4. Three-State Mixings

An interesting possibility is that three f_0's in the $1.4 - 1.7$ GeV region are admixtures of the three isosinglet states gg, $s\bar{s}$, and $n\bar{n}$[13]. At leading order in the glueball-$q\bar{q}$ mixing, ref[13] obtained

$$N_G|G\rangle = |G_0\rangle + \xi(\sqrt{2}|n\bar{n}\rangle + \omega|s\bar{s}\rangle)$$
$$N_s|\Psi_s\rangle = |s\bar{s}\rangle - \xi\omega|G_0\rangle$$
$$N_n|\Psi_n\rangle = |n\bar{n}\rangle - \xi\sqrt{2}|G_0\rangle \quad (3)$$

where the N_i are appropriate normalisation factors, $\omega \equiv \frac{E(G_0) - E(d\bar{d})}{E(G_0) - E(s\bar{s})}$ and the mixing parameter $\xi \equiv \frac{\langle d\bar{d}|V|G_0\rangle}{E(G_0) - E(d\bar{d})}$. The analysis of ref[14] suggests that the $gg \to q\bar{q}$ mixing amplitude manifested in $\psi \to \gamma R(q\bar{q})$ is $O(\alpha_s)$, so that qualitatively $\xi \sim O(\alpha_s) \sim 0.5$. Such a magnitude implies significant mixing in eq.(3) and is better generalised to a 3×3 mixing matrix. Ref.[12] defines this to

be

$$\begin{matrix} m_G^0 & z & \sqrt{2}z \\ z & m_s^0 & 0 \\ \sqrt{2}z & 0 & m_n^0 \end{matrix}$$

where $z \equiv \xi \times (E(G_0) - E(d\bar{d}))$ in the notation of ref.[13].

Mixing based on lattice glueball masses lead to two classes of solution of immediate interest:
(i)$\omega \leq 0$, corresponding to G_0 in the midst of the nonet[13]
(ii)$\omega > 1$, corresponding to G_0 above the $q\bar{q}$ members of the nonet[12].

We shall denote the three mass eigenstates by R_i with $R_1 = f_0(1370)$, $R_2 = f_0(1500)$ and $R_3 = f_0(1710)$, and the three isosinglet states ϕ_i with $\phi_1 = n\bar{n}$, $\phi_2 = s\bar{s}$ and $\phi_3 = gg$ so that $R_i = f_{ij}\phi_i$.

There are indications from lattice QCD that the scalar $s\bar{s}$ state, in the quenched approximation, may lie lower than the scalar glueball [28,12]. Weingarten[12] has constructed a mixing model based on this scenario. The input "bare" masses are $m_n^0 = 1450; m_s^0 = 1516; m_G^0 = 1642$ and the mixing strength $z \equiv \xi \times (E(G_0) - E(d\bar{d})) = 72$ MeV. The resulting mixtures are

	$f_{i1}^{(n)}$	$f_{i2}^{(s)}$	$f_{i3}^{(G)}$
$f_0(1370)$	0.87	0.25	−0.43
$f_0(1500)$	−0.36	0.91	−0.22
$f_0(1710)$	0.34	0.33	0.88

It is suggested, but not demonstrated, that the decays of the $f_0(1500)$ involve significant destructive interference between its gluonic and $s\bar{s}$ components whereby the $K\bar{K}$ suppression and 2π, 4π enhancements are explained.

Recent data on the decay $f_0(1500) \to K\bar{K}$[31] may be interpreted within the scheme of ref[13] as being consistent with the G_0 lying between $n\bar{n}$ and $s\bar{s}$ such that the parameter $\omega \sim -2$. (In this case the $\eta\eta$ production is driven by the gluonic component of the wavefunction almost entirely,see ref[13]). If for illustration we adopt $\xi = 0.5 \sim \alpha_s$, the resulting mixing amplitudes are

	$f_{i1}^{(n)}$	$f_{i2}^{(s)}$	$f_{i3}^{(G)}$
$f_0(1370)$	0.86	0.13	−0.50
$f_0(1500)$	0.43	−0.61	0.61
$f_0(1710)$	0.22	0.76	0.60

The solutions for the lowest mass state in the two schemes are similar, as are the relative phases and qualitative importance of the G component in the high mass state. Both solutions exhibit destructive interference between the $n\bar{n}$ and $s\bar{s}$ flavours for the middle state.

This parallelism is not a coincidence. A general feature of this three way mixing is that in the limit of strong mixing the central state tends towards flavour octet with the outer (heaviest and lightest) states being orthogonal mixtures of glueball and flavour singlet, namely

$$
\begin{array}{ll}
f_0(1370) & |q\bar{q}(\mathbf{1})\rangle - |\mathbf{G}\rangle \\
f_0(1500) & |q\bar{q}(\mathbf{8})\rangle + \epsilon|\mathbf{G}\rangle \\
f_0(1710) & |q\bar{q}(\mathbf{1})\rangle + |\mathbf{G}\rangle
\end{array}
$$

where $\epsilon \sim \xi^{-1} \to 0$.

In short, the glueball has leaked away maximally to the outer states even in the case (ref[13]) where the bare glueball (zero mixing) was in the middle of the nonet to start with. The leakage into the outer states becomes significant once the mixing strength (off diagonal term in the mass matrix) becomes comparable to the mass gap between glueball and $q\bar{q}$ states (i.e. either $\xi \geq 1$ or $\xi\omega \geq 1$). Even in the zero width approximation of ref[13] this tends to be the case and when one allows for the widths being of $O(100)$MeV while the nonet masses and glueball mass are spread over only a few hundred MeV, it is apparent that there will be considerable leakage from the glueball into the $q\bar{q}$ nonet. It is for this reason, *inter alia*, that the output of refs[13] and [12] are rather similar. While this similarity may make it hard to distinguish between them, it does enable data to eliminate the general idea should their common implications fail empirically.

If we make the simplifying assumption that the photons couple to the $n\bar{n}$ and $s\bar{s}$ in direct proportion to the respective e_i^2 (i.e. we ignore mass effects and any differences between the $n\bar{n}$ and $s\bar{s}$ wavefunctions), then the corresponding two photon widths can be written in terms of these mixing coefficients:

$$
\Gamma(R_i) = |f_{i1}\frac{5}{9\sqrt{2}} + f_{i2}\frac{1}{9}|^2\Gamma, \tag{4}
$$

where Γ is the $\gamma\gamma$ width for a $q\bar{q}$ system with

$e_q = 1$. One can use eq. (4) to evaluate the relative strength of the two photon widths for the three f_0 states with the input of the mixing coefficients[14]. If we ignore mass dependent effects, these lead to the results in eqn.2. We anticipate $f_0(1500) \to \gamma\gamma \sim 0.3 \pm 0.2$ keV [13] or ~ 0.1 keV [12]. Both schemes imply $\Gamma(f_0(1710) \to \gamma\gamma) = O(1)$ keV.

This relative ordering of $\gamma\gamma$ widths is a common feature of mixings for all initial configurations for which the bare glueball does not lie nearly degenerate to the $n\bar{n}$ state. As such, it is a robust test of the general idea of $n\bar{n}$ and $s\bar{s}$ mixing with a lattice motivated glueball. If, say, the $\gamma\gamma$ width of the $f_0(1710)$ were to be smaller than the $f_0(1500)$, or comparable to or greater than the $f_0(1370)$, then the general hypothesis of significant three state mixing with a lattice glueball would be disproven. The corollary is that qualitative agreement may be used to begin isolating in detail the mixing pattern.

The production of these states in $\psi \to \gamma f_0$ also shares some common features in that $f_0(1710)$ production is predicted to dominate. The analysis of ref.[14] predicts that

$$
br(J/\psi \to \gamma \Sigma f_0) \geq (1.5 \pm 0.6) \times 10^{-3}. \tag{5}
$$

In [13] the $q\bar{q}$ admixture in the $f_0(1500)$ is nearly pure flavour octet and hence decouples from gg. This leaves the strength of $br(J/\psi \to \gamma f_0(1500))$ driven entirely by its gg component at about 40% of the pure glueball strength. This leads to eqn.1 which appears to be consistent with the mean of the world data ([17,20,14]).

Thus, in conclusion, both these mixing schemes imply a similar hierachy of strengths in $\gamma\gamma$ production which may be used as a test of the general idea of three state mixing between glueball and a nearby nonet. Prominent production of $J/\psi \to \gamma f_0(1710)$ is also a common feature. When the experimental situation clarifies on the $J/\psi \to \gamma f_0$ branching fractions, we may be able to distinguish between the case where the glueball lies within a nonet, ref[13], or above the $s\bar{s}$ member, ref[12].

In the former case this $G_0 - q\bar{q}$ mixing gives a destructive interference between $s\bar{s}$ and $n\bar{n}$ whereby decays into $K\bar{K}$ are suppressed. How-

ever, even in the case where the $s\bar{s}$ lies below the G_0 we expect that there will be $K\bar{K}$ destructive effects due to mixing not only with the $s\bar{s}$ that lies below G_0 (as in ref.[12]) but also with a radially excited $n\bar{n}$ lying above it (not considered in ref.[12]). Unless G_0 mixing with the radial state is much suppressed, this will give a similar pattern to that of ref.[13] though with more model dependence due to the differing spatial wavefunctions for the two nonets.

5. The Hybrid Candidates

When the gluon degrees of freedom are excited in the presence of $q\bar{q}$ one has so called "hybrid" states. In lattice QCD and/or models one expects these states (denoted π_g, D_g, ψ_g to mean gluonic excitation with overall flavour quantum numbers of a π, D or $c\bar{c}$ etc) to occur with masses $\pi_g \sim$ 1.8 GeV, $D_g \sim 3$ GeV, $\psi_g \sim 4$ GeV. There are tantalising sightings of an emerging spectroscopy as I shall now review.

It is well known that hybrid mesons can have J^{PC} quantum numbers in combinations such as $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$ etc. which are unavailable to conventional mesons and as such provide a potentially sharp signature.

It was noted in ref.[32] and confirmed in ref.[33] that the best opportunity for isolating exotic hybrids appears to be in the 1^{-+} wave where, for the I=1 state with mass around 2 GeV, partial widths are typically

$$\pi b_1 : \pi f_1 : \pi\rho = 170 \, MeV : 60 \, MeV : 10 \, MeV \quad (6)$$

The narrow $f_1(1285)$ provides a useful tag for the $1^{-+} \to \pi f_1$ and ref.[36] has recently reported a signal in $\pi^- p \to (\pi f_1)p$ at around 2.0 GeV that appears to have a resonant phase.

Note the prediction that the $\pi\rho$ channel is not negligible relative to the signal channel πf_1 thereby resolving the puzzle of the production mechanism that was commented upon in ref. [36]. This state may also have been sighted in photoproduction [37] with $M = 1750$ and may be the $X(1775)$ of the Data Tables, ref.[1]. There has also been recent claim for a possible exotic $J^{PC} = 1^{-+}$ around 1.4GeV decaying into $\pi\eta$[38] which is also reported from LEAR[40]. There is

also a signal around 1.6GeV in $\pi\eta'$[39]. The experimental situation here needs to be settled before the lattice predictions are confronted directly but there does seem a likelihood that we can anticipate the emergence of a hybrid spectroscopy to be compared with the lattice and QCD inspired models.

A recent development is the realisation that even when hybrid and conventional mesons have the **same** J^{PC} quantum numbers, they may still be distinguished [33] due to their different internal structures which give rise to characteristic selection rules. When conventional quantum numbers such as 0^{-+} are analysed on the lattice, it is found that the conventional mesons, such as the π, have considerable signal[41]. In order to separate the genuine π from the hybrid signal on the lattice it would be interesting to exploit the different spin content of the hybrid and ground state configurations.

Turning to the 0^{-+} wave, the VES Collaboration at Protvino and BNL E852 both see a clear 0^{-+} signal in diffractive $\pi N \to \pi\pi\pi N$. [35]. Its mass and decays typify those expected for a hybrid: $M \approx 1790$ MeV, $\Gamma \approx 200$ MeV in the $(L = 0) + (L = 1)$ $\bar{q}q$ channels $\pi^- + f_0$; $K^- + K_0^*$, $K(K\pi)_S$ with no corresponding strong signal in the kinematically allowed $L = 0$ two body channels $\pi + \rho$; $K + K^*$. This confirms the earlier sighting by Bellini et al[44], listed in the Particle Data group[1] as $\pi(1770)$.

The resonance also appears to couple as strongly to the enigmatic $f_0(980)$ as it does to $f_0(1300)$, which was commented upon with some surprise in ref. [35]. This may be natural for a hybrid at this mass due to the predicted dominant KK_0^* channel which will feed the $(KK\pi)_S$ (as observed [35]) and hence the channel $\pi f_0(980)$ through the strong affinity of $K\bar{K} \to f_0(980)$. Thus the overall expectations for hybrid 0^{-+} are in line with the data of ref.[35].

This π_g is, accidentally, degenerate with the D and so may affect the Cabibbo suppressed decays of the latter[24]. A comparison between decays of π_g[34] and the Cabibbo suppressed decays of D as measured by E687 collaboration at Fermilab, show some parallels. Is is possible that this accidental degeneracy could give a non-

perturbative enhancement of CP violation in the D system[24,42]. To test further the idea that the π_g affects D decays, one should search in D decays for channels that have shown up in π_g decay. For example: if π_g is a guide, then $D \to K\bar{K}\pi$ in $S-$wave will be significant and $D \to \eta\eta\pi^-$ should occur at about 50% intensity of $\pi^+\pi^-\pi^-$. Finally, the glueball candidate f_0 (1500) should occur in $D \to \pi f_0$ (1500).

This is an instructive example of where light flavour spectroscopy can affect the dynamics of heavy flavour decays. In the final section I shall turn to heavy flavours. There have been interessting developments both in the lattice, for hybrid charmnonium, and in phenomenology related to B decays as a possible source of the hybrid charmonia and of heavy glueballs.

5.1. Hybrid Charmonium and missing charm

The decay $B \to K + (c\bar{c})$ produces the $(c\bar{c})$ dominantly in a colour 8. It may thus be an entree into the hybrid charmonium sector. Furthermore the lightest such states are predicted by lattice QCD[43] to occur around 4.1 ± 0.1 GeV whereby $B \to K + \psi_g$ may be favoured. Finally, in models, such states decay strongly into DD^{**}, for which the threshold is 4.3 GeV, and not into $D\bar{D}, DD^*, D^*\bar{D}^*$. Consequently their preferred decays could be
a) cascades to ψ, χ, η_c, h_c + light hadrons
b) decays to light hadrons via resonant glueballs, namely $(c\bar{c}_8 g \to g^* g \to$ light hadrons. As such this could be an entree into the spectrum of glueballs, predicted by lattice QCD to lie between 2-4 GeV and including exotic states $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$. This has been suggested by ref.[10]

In summary: the lattice predictions that the lightest glueball is a scalar merge tantalisinngly with the discovery of an enigmatic $f_0(1500)$ and with the possibility that the $f_J(1710)$ contains a significant $J = 0$ component. They are produced in the right mass region, according to the lattice, and in the right processes, according to intuition developed from knowledge of hadron dynamics. Important now is to understand the dynamics behind the central production kinematic filter that

appears to distinguish the glueball candidates from established $q\bar{q}$ mesons. Finally, to complete the scalar nonet, we need to establish the $s\bar{s}$ member. The $f_0(980)$ may be the remnant of this state, shifted to $K\bar{K}$ threshold by its S-wave coupling to mesons, or there may be a state to be established around $1700 - 1800$ MeV: the spin of the $f_J(1710)$ and its relation to the $f_0(1500)$ is critical in this respect. The decays $D_s \to \pi K\bar{K}$ and the production via $\gamma\gamma \to f_0 \to K\bar{K}$ in contrast to $\gamma\gamma \to f_0 \to \pi\pi$ promise the most direct resolution of this question. Finally, the decays of $B \to K+$ light hadrons may reveal intersting new dynamics up to ~ 4 GeV in mass.

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